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Study of the production of a low emittance muon beam for the LEMMA project

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Summary. — The Low EMittance Muon Accelerator (LEMMA) is a concept for a positron-driven muon source for a future multi-TeV muon collider, which aims to produce a low emittance muon beam via positron-electron annihilation overcoming the need to cool the beam. I will describe the principles of this concept together with the first results of the muon production studies. I will also discuss the 6D emittance evolution through the production line for the single-target configuration. These studies have been performed with a novel simulation code developed for this purpose.

1. – The LEMMA project

There is great interest in the use of muon beams in high-energy physics experiments, for precision measurements, neutrino physics, rare decays and for future muon colliders. This last option offers great potential to extend the energy limit for a leptonic collider in the multi-TeV region, as the power emitted as synchrotron radiation from a muon is a factor $(m_e/m_\mu)^4$ lower with respect to that of an electron beam of the same energy, therefore allowing to reach higher energies [1].

The customary way to produce muon beams is to obtain them from the decay of kaons or pions produced from the interaction of a proton source with a target. A design study for a muon collider using this scheme has been performed by the Muon Accelerator Program (MAP) [2]. The main characteristics of such muon beams are the high intensity but also the large beam emittance due to the kinematics of the production, as pions are produced with high momentum spread, and therefore require a 6D emittance cooling system. While transverse cooling has been tested by the MICE experiment [3], longitudinal cooling has not been put to the test yet.

The Low EMittance Muon Accelerator (LEMMA) [4, 5] proposes a novel approach in the production of muons by impinging a positron beam of $\sim$45 GeV on the atomic electrons of a target, resulting in a center-of-mass energy of $\sim 0.212\,\mathrm{GeV}/c^2$, just above the threshold for muon production via electron-positron annihilation $e^+e^- \to \mu^+\mu^-$, as shown in the left picture of fig. 1.

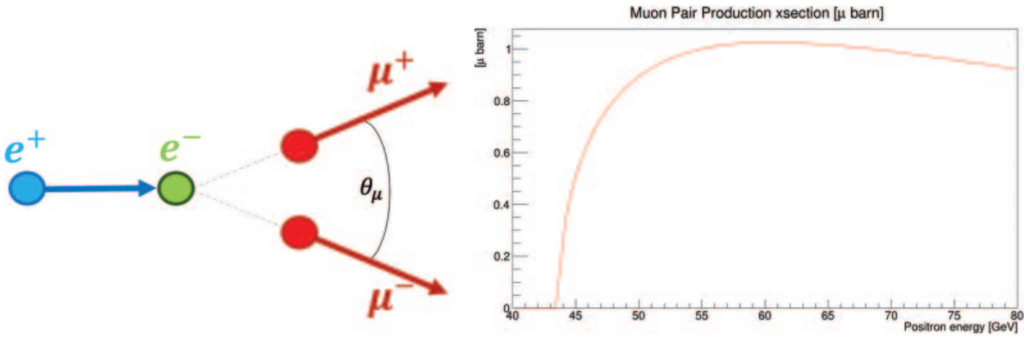

Fig. 1. – Left: schematic of the muon pair production reaction. Right: cross-section of muon production via electron-positron annihilation as a function of the energy of the positron beam.

The most important features of the produced muon beam are:

- *very small emittance*, because the beam size is the same of the impinging positron beam, and the divergence is strictly dependent on the energy in the center of mass ($\sim$500 μrad at $E_{e^+} = 45\,\text{GeV}$)
- 500 μs *lifetime* in the laboratory frame due to the high production energy of the muon beam (22.5 GeV $\rightarrow \gamma \sim 200$)

In particular, the low emittance is the key characteristic of this positron driven source, as it eliminates the need for a 6D cooling system, allowing in principle to reach sufficiently high values of luminosity even if the muon production cross-section is $\sim$1 μb to be compared with $\sim$1 mb for the proton driven case. The muon pair production via e^+e^- annihilation cross-section as a function of the positron beam energy is shown in the right plot of fig. 5.

In addition, the lifetime of $\sim$500 μs allows for the design of a muon accumulation system in order to increase the number of particles per bunch at the collider. In the LEMMA design —shown in fig. 2— the target (yellow) is embedded in a section common to the positron line (red) and two muon accumulator rings (blue), one for μ^+ and one for μ^-. Positron bunches are separated by a distance equal to the circumference of the two accumulators ($\sim$150 m), so that the positron bunch will arrive at the target together

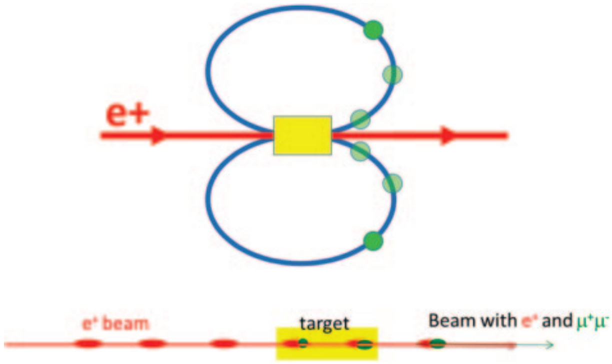

Fig. 2. – Concept of the muon production and accumulation process in LEMMA.

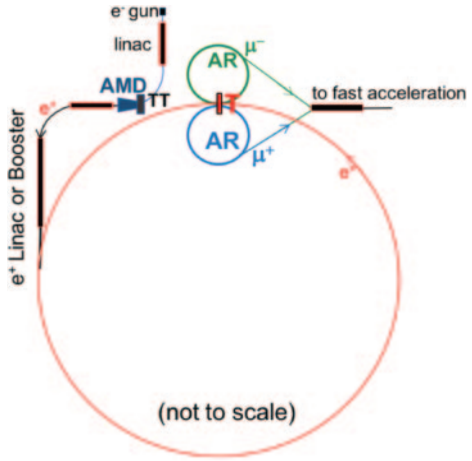

Fig. 3. – Multi-pass scheme conceptual design.

with the two muon bunches produced by the previous positron bunch.

The three bunches will co-propagate through the target, and while doing so the positrons will produce new muon pairs in the same phase-space of the pre-existing muon bunches. This way the only emittance increase will be due to the multiple scattering process of several passages through the target of the accumulated muons. Considering two rings of $\sim$150 m circumference and the muon lifetime in the laboratory frame of $\sim$500 μs, the accumulation process can be performed for about 1000 turns in the rings.

Several designs for the LEMMA production are being studied [6], but they can be divided in two families:

- *Multi-pass scheme*: The production region is embedded in the positron ring. In this design (see fig. 3) the same positron bunches pass through the target several times. The main advantage of this scheme is to relax the requirement on the positron source, but on the other hand the target must be very thin, of the order of $O(0.01X_0)$, or the positron bunch will be lost almost immediately after passing through the target. On the other hand, a thin target means few electrons and therefore a small number of produced muons.

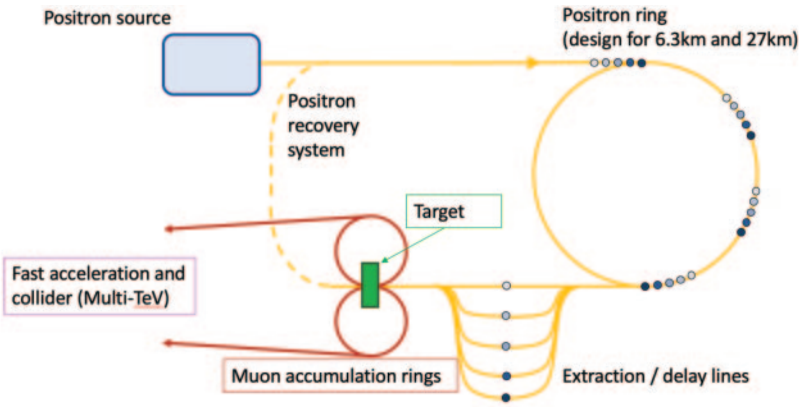

Fig. 4. – Single-pass scheme conceptual design.

- *Single-pass scheme*: The production region is outside the positron ring, so the positron bunch is extracted from the ring and sent to the target via a transfer line [7]. In this design (see fig. 4) the positron bunches will pass only once through the target, so a thicker target can be used $O(1X_0)$, increasing the number of produced muons.

  After passing through the thick target the surviving positron bunch cannot be immediately re-injected in the positron ring. An embedded positron source that can profit from the high number of photons produced by the e^+ passing through the target to produce new positrons impinging on a tungsten target is under study. To further increase the number of muon produced per passage, a system of positron delay lines can be implemented in order to send to the target several e^+ bunches at the same time. The main drawback of this single-pass scheme is the high positron production rate which is required.

Presently, the most interesting scheme seems to be the single-pass because it allows to produce an higher number of μ^+ μ^- couples. Therefore, the studies shown in the next section focus on this single-pass scheme.

2. – Muon production studies

The number of μ^+ μ^- couples produced by a positron beam impinging on a target of a given material and length is given by

$$n(\mu^+\mu^-) = n_{e^+} \cdot \frac{Z}{A} N_A \rho L \cdot \sigma(e^+e^- \to \mu^+\mu^-), \tag{1}$$

where n_{e^+} is the number of positrons in the bunch, $\sigma(e^+e^- \to \mu^+\mu^-)$ is the muon production cross-section (dependent on the positron beam energy, as shown in fig. 5(left)), N_A is the Avogadro number, while L, ρ, Z and A are, respectively, length, density atomic number and weight of the target.

Figure 5(center) and (right) show the divergence and the energy spread of a muon beam produced by a point-like monochromatic positron beam of a given energy.

The best trade-off between produced muons and their emittance was found to be for light material targets with $\sim O(1X_0)$ length and a positron beam energy of 45 GeV. The chosen material for the following simulation is beryllium, as it shows best performances in terms of numbers of muons produced between solid targets.

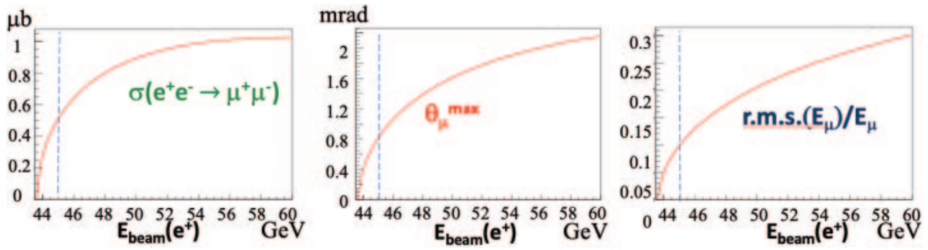

Fig. 5. – Muon production cross-section (left), divergence (center) and energy spread (right) of the produced muons as a function of the positron beam energy.

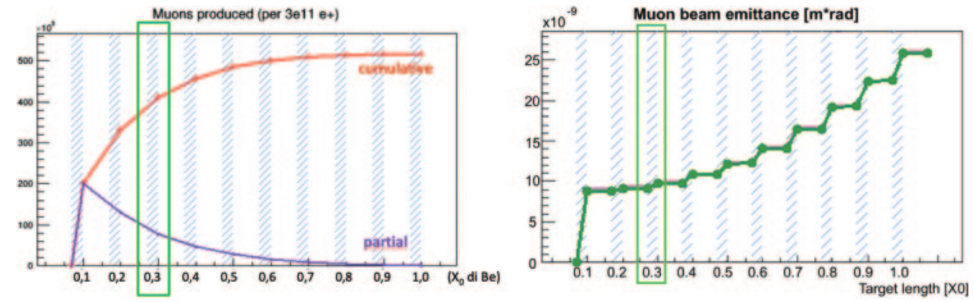

Fig. 6. – Left: muon pairs produced as a function of the target length (in orange the total number of muons produced from the start of the target, in purple the muons produced in that $0.1X_0$ long slice). Right: emittance of the produced muon beam as a function of the target length, in green the horizontal and in magenta the vertical emittance (not clearly visible because behind the green line).

In order to determine the optimal length of the beryllium target, a simulation has been performed using a custom Monte Carlo code named MUFASA (MUon FAst Simulation Algorithm) benchmarked with Geant4 and FLUKA, which also supports the interface with the particle tracking code MADX/PTC. We present here the interaction of a 45 GeV positron beam, with beamsize $\sigma_x = 20\,\mu\text{m}$ and $\epsilon_x = 70\,\text{pm}$ with a beryllium target $1X_0$ long. The information on the number of produced muons and their 6-D coordinates is acquired every $0.1X_0$. Figure 6 shows the results of this study. The left plot shows that the resulting muon beam emittance is mostly constant for the first third of the target, then the contribution of the multiple scattering is dominant. In addition, the muon production after about $0.4X_0$ starts to be negligible; this occurs because the positrons lose energy in the target due to Bremsstrahlung, and after passing through this thick target most of them are under the production threshold of 43.7 GeV. Therefore, from this study the optimal target length is $0.3X_0$, which yields a production efficiency of about 1.3×10^{-6}.

An interesting alternative to the beryllium target is liquid H2. Figure 7 shows the result of the simulation under the same conditions but using a liquid-hydrogen target instead on beryllium. It appears clearly that the muon production is double with respect to the beryllium while the muon beam emittance is the same. However, being one

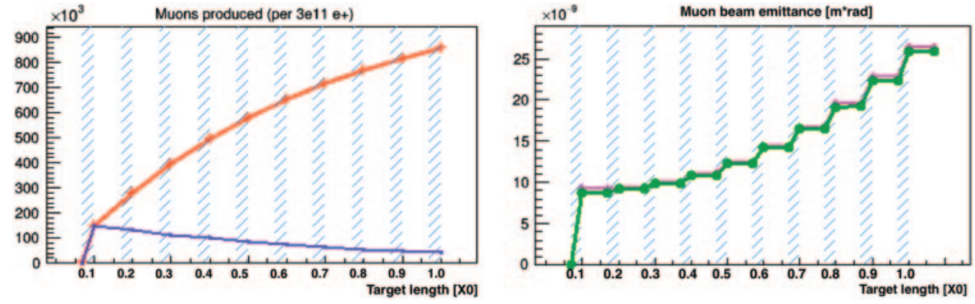

Fig. 7. – Muon pairs produced and transverse emittance as a function of the target length for a LH2 target.

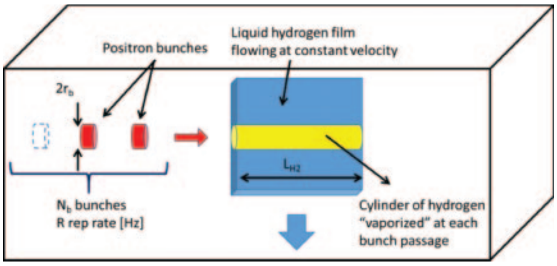

Fig. 8. – Scheme of the liquid target cell.

radiation length of liquid Hydrogen much longer than that of beryllium, *i.e.*, $X_0(LH2) = 8.88\,\text{m}$, instead of $X_0(\text{Be}) = 0.35\,\text{m}$, a target as long as 2.66 m would be needed, which seems an unpractical solution.

In addition, liquid hydrogen is vaporized in the interaction with the positron beam. This means that the target must flow in the interaction region at a constant velocity, so that the material vaporized from the first positron bunch is replaced before the arrival of the next bunch. A conceptual design of this setup is shown in fig. 8. The target vaporization would be a further topic to be addressed with this solution.

3. – Conclusions

In this work the LEMMA conceptual design for a low emittance muon source has been described. The main issue with this scheme is the low production rate due to the small cross-section of the process of interest. In order to overcome this, it is necessary to optimize the target choice in order to maximize muon production while keeping the emittance low. In this regard, the results for a first study on thick target have been shown for beryllium and liquid-hydrogen targets, highlighting advantages and disadvantages for the two cases. Upcoming studies will focus on the development of the muon accumulator rings lattice and start-to-end simulations for the accumulation process in order to produce a full table of parameters for this scheme.

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